Deep-Water Ambient Noise Profiling; Marine Sediment Acoustics; and Doppler Geo-Acoustic Spectroscopy

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LONG-TERM GOALS

1) <u>Deep-water ambient noise profiling</u> Profile the spectral, temporal and spatial properties of broadband (3 Hz – 30 kHz) ambient noise from the surface to the bottom of the deepest ocean. Develop theoretical models of the second-order spatial statistics of the noise.

2) <u>Marine sediment acoustics</u> Develop a unified, physics-based model of sound wave and shear wave propagation in saturated, unconsolidated marine sediments.

3) <u>Doppler geo-spectroscopy</u> Develop the use of a light aircraft as a sound source for performing inversions for the geo-acoustic parameters of the seabed in shallow water.

OBJECTIVES

1) The scientific objective of the deep-water ambient noise research is to measure the second-order spatial statistics of the ambient noise in the deepest oceans as a function of depth, from the sea surface to the seabed. Regions of interest include the Challenger Deep in the Mariana Trench (11 km), the Tonga Trench (9 km), and the Puerto Rico Trench (8 km). Environmental and system data will also be depth-profiled, including temperature, salinity, pressure and sound speed, along with all system motions (translational and rotational). Theoretical modeling of the spectral, spatial and temporal properties of the ambient noise will also be performed.

2) The sediment acoustics research is aimed at developing a unified theory of wave propagation in marine sediments in the form of the dispersion relations for the compressional and shear waves. Besides the frequency dependencies of the wave speeds and attenuations, these expressions will also return the dependence of the wave parameters on the mechanical properties of the sediment, namely porosity, density, grain size and overburden pressure.

3) The Doppler geo-acoustic spectroscopy technique, in which an aircraft is used as a sound source, is in support of the sediment acoustics research, providing a means of measuring the sound speed in the sediment at frequencies between 80 and 1000 Hz.

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APPROACH

1) <u>Deep-water ambient noise profiling</u> A deep-diving autonomous instrument platform known as
    Deep Sound has been designed and developed by my research group. Deep Sound consists of a
    Vitrovex glass sphere housing a microprocessor for system control, along with data acquisition
    and storage electronics. External to the sphere are several hydrophones (bandwidth 3 Hz – 30
    kHz, calibrated to equivalent depths of 12 km), which may be arranged in various vertical and
    horizontal configurations, and an environmental sensor package (CTD and sound velocimeter).
    The system is untethered, descending under gravity and, after releasing a drop weight at a pre-
    assigned depth, returning to the surface under buoyancy. Throughout the descent and ascent, at
    0.6 m/s, acoustic and environmental data are continuously recorded. Three beacons (high intensity
    strobe, radio antenna, and Argos GPS) aid recovery of the system. Numerous fail-safe devices are
    onboard, intended to ensure that the weight is indeed dropped, thus allowing the system to return
    to the surface.

    In conjunction with the experimental work using Deep Sound, I am developing a series of
    analytical models for the spatial coherence and cross-correlation properties of ambient noise in
    the deep ocean. These models address the directionality and bandwidth of the noise as they affect
    the cross-correlation function. The models will help us interpret the two-point measurements of
    noise recovered from Deep Sound.

2) <u>Marine sediment acoustics</u> My theoretical approach involves the development of the
    compressional and shear wave dispersion relations, based on inter-granular interactions. In the
    latest version of the grain-shearing theory, the viscosity of the pore fluid is included in the
    analysis, which leads to low frequency (< 10 kHz) compressional wave behavior that is in accord
    with measurements made during the ONR-supported Sediment Acoustics Experiment 1999 (SAX
    99). At higher frequencies, above 10 kHz, the effect of pore fluid viscosity is negligible and again
    the new theory fits the compressional wave data. Thus, the latest version of the theory fits all the
    available compressional wave and shear wave data from the SAX 99 experiments and elsewhere.

3) <u>Doppler geo-acoustic spectroscopy</u> A light aircraft flown at low level over the ocean acts as a
    sound source, which is used as the basis of an inversion technique for recovering the speed of
    sound in the seabed. The sound from the aircraft consists of a series of harmonics, typically 80,
    160, 240, . Hz. Some of this acoustic energy penetrates the sea surface and reflects off the seabed,
    acquiring information about the sediment in the process. From recordings made on hydrophones
    in the water column and/or buried in the seabed, an inversion is performed which returns the
    phase speed of the compressional wave in the sediment. Once the compressional speed is known,
    most of the remaining geo-acoustic parameters are estimated using the correlations provided by
    the grain-shearing theory.

WORK COMPLETED

Three versions of Deep Sound, designated the Mk. I, Mk. II and Mk. III, have been designed and built.
The Mk. I has been deployed a number of times to great depths, approximately 6 km in the Philippine
Sea and 9 km in the Mariana Trench, and is now showing signs of wear. Spalling of the glass sphere
around the internal equator has occurred as a result of the compression due to the extreme hydrostatic
pressure encountered at depth. Mk. I has now been retired and is no longer operational.

Deep Sound Mk. II was deployed in the Mariana Trench in November 2009, where it successfully recorded ambient noise on vertically and horizontally aligned hydrophones from the surface to a depth of 9 km over the acoustic frequency band from 3 Hz to 30 kHz.

Deep Sound Mk. III is the most sophisticated of the three systems, capable of descending to a depth of 11 km. On board is a sound velocimeter, a sing-around instrument which records sound speed directly, for comparison with the computed values from the CTD. This allows us to test the validity of sound speed algorithms for the extreme pressures found at the bottom of ocean trenches.

An attempt was made to deploy Deep Sound Mk. II and III in the Mariana Trench in July 2011, to depths of 9 km and 11 km, respectively. Working with a National Geographic group, a research vessel, the M/V Super Emerald, was chartered out of Saipan (at no cost to us) and used for the four-day deployment. Weather conditions were bad, with heavy seas and storms throughout the time at sea. The M/V Super Emerald was not well suited to the task, and at least one system (not one of ours) was lost. We should have been the last to deploy but decided against putting our systems in the water, given the extreme problems the other groups had experienced.

In early September 2012, Deep Sound Mk. II & III were deployed in the Tonga Trench from the R/V Roger Revelle. The hydrophones on board each of the systems were fitted with newly designed flow shields, intended to suppress the effects of turbulent flow generated by the motion of Deep Sound through the water column. Both Deep Sound systems descended to a depth of approximately 9 km, stayed on the bottom for an extended period, and returned to the surface after about 10 hours, all the while collecting broadband (3 Hz – 30 kHz) ambient noise data, along with environmental and system data.

An invited paper[1] on the Deep Sound has been published in a special issue of the *Journal of the Marine Technology Society* commemorating the Golden Anniversary of the dive of the manned submersible *Trieste* to the bottom of the Challenger Deep. A theoretical paper[2] on the directionality of ambient noise and its effects on the two point (vertical and horizontal) cross-correlation function has been published in the *Journal of the Acoustical Society of America* (JASA). Another paper[3] has been published in JASA in which a theoretical model of a three–dimensional noise field is developed. The model represents noise from a storm, showing a strong peak in the horizontal combined with significant vertical directionality. This is relevant to some of the data that were collected in the Philippine Sea, by Deep Sound Mk. I as an intense storm passed more or less overhead. An analysis of the storm data is described in a paper[4] that is currently under review at JASA. Wind-driven noise, also recorded during one of the deployments of Deep Sound Mk. I in the Philippine Sea, is described in another paper[5] that has been conditionally accepted for publication in JASA. A fifth, theoretical paper[6] has been published in JASA on band-limited noise, and the effects the filtering has on the cross-correlation function.

RESULTS

Deep Sound Mk. I and II were both deployed to a depth of 9 km in the Mariana Trench in November 2009, where they continuously recorded ambient noise data, along with environmental information, on the descent and the ascent. The spectral level of the noise was found to increase slightly with increasing depth, even through the critical depth, by an amount that depends on frequency.

During an earlier deployment of Mk. I, in the Philippine Sea in May 2009, the sound of several rainstorms was recorded and is clearly visible in the spectrograms. An analysis shows that the rain noise is highy directional, with a strong lobe near the downward vertical[4]. Through an inversion, the storm was tracked across the sea surface, and some verification of the results was provided by ground truth measurements of rainfall rates made on board the research ship, the R/V Kilo Moana, supporting the deployment.

Wind-driven noise was recorded on two vertically aligned hydrophones during one of the deployments of Deep Sound Mk. I in the Philippine Sea in May 2009. The vertical coherence of the noise[5] is in excellent agreement with the theory of Cron & Sherman[7] for surface-generated noise in a semi-infinite, isovelocity ocean. This implies that the noise was essentially all downward traveling, suggesting that reflections from the sea bed, even in the proximity of the bottom, made a negligible contribution to the noise field. A comparison of the measured noise coherence at a depth of 3 km with Cron & Sherman's theory[7] is shown in Fig. 1.

My theoretical treatment of cross-correlation in spatially homogeneous, anisotropic ambient noise fields identifies the conditions necessary for extraction of the Green's function from directional noise[2], on the assumption that the noise spectrum is white. Several examples of anisotropy are considered in the analysis, including Cron and Sherman's deep-water, downward-traveling ambient noise field[7]. In that particular case, because of the surface reflection, the Green's function depends on the depth of the transducers, whereas the cross-correlation function is independent of absolute position in the water column. It is, therefore, impossible to recover the Green's function from the noise, because the surface-reflected component will always be absent from the cross-correlation function. It is possible, however, to recover the sound speed in the medium from the noise, since the cross-correlation function exhibits sharp features at correlation delay times numerically equal to the travel time between the sensors.

In a related analysis, the effect on the cross-correlation function of band-limiting the ambient noise was investigated theoretically[6]. Horizontal and vertical alignments of the hydrophones were considered in the context of isotropic noise and deep-water noise, as represented by the Cron and Sherman[7] model. The focus of the analysis is on sensor separations that are very much greater than the longest wavelength (associated with the lowest frequency) in the pass-band. It turns out that, if the filter has a low-frequency roll-off, scaling as frequency to the power of $2n$, this acts as a differentiator of order $2n$ on the cross-correlation function. In general, cross-correlation functions of filtered ambient noise do not exhibit delta functions that could be identified with the Green's function, but they may possess sharp features that allow the travel time between the sensors to be determined. From the travel time, it is possible to recover the sound speed in the medium. The mechanism that gives rise to these sharp features in the cross-correlation function is, however, quite different from that responsible for the appearance of delta functions in the derivative of the cross-correlation function of isotropic white noise.
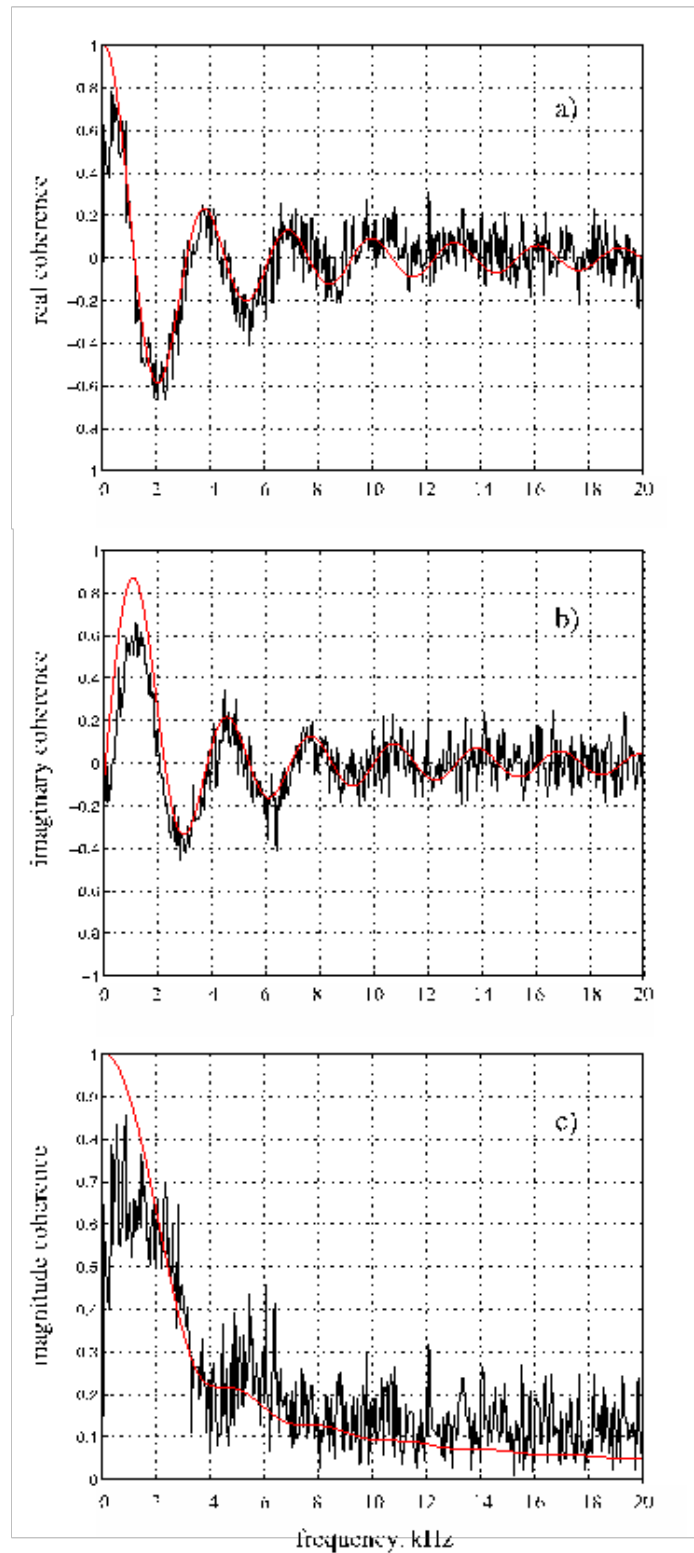
Fig. 1 Vertical coherence function at depth of 3 km on the ascent, Phillipine Sea. The jagged black line represents data, the smooth red line is Cron and Sherman's theory. a) Real part, b) imaginary part, c) magnitude.

5

In order to interpret the directional features of the storm noise recorded by Deep Sound Mk. I during the Philippine Sea deployment, a theoretical model of a three-dimensional noise field showing strong horizontal and vertical directionality has been developed[3]. The horizontal component of the noise is represented by a von Mises distribution[8], taken from directional statistics, whilst the vertical component, associated with wave-breaking, is consistent with a set of dipoles distributed randomly across the sea surface. Expressions for the spatial coherence and cross-correlation of the noise at two horizontally aligned hydrophones are derived. Through a couple of parameters, the intensity and angular position of the storm can be adjusted, allowing the spatial statistics of the noise for various geometrical configurations to be investigated.

IMPACT/APPLICATIONS

Deep Sound Mk. III is modular allowing the hydrophones in the current configuration to be replaced with any other type of sensor, for instance, dissolved oxygen, carbon dioxide or hydrocarbon sensors. Mk. III can even profile the local current vector, since the on board inertial navigation system tracks translational (and rotational) motion due to advection from the current.

My theory of wave propagation in marine sediments[9] has a variety of applications, particularly in regard to acoustic inversions for the geo-acoustic parameters of the seabed. Charles Holland and Ross Chapman are independently using the theory to develop numerical inversion schemes for recovering the properties of the bottom.

Michael Porter is developing a suite of 3-D acoustic propagation models. He is using my analytical models[10, 11] of the penetrable wedge and the conical seamount for comparison with his numerical results.

A conference was held recently on "Basic Science and the Future Warfighter" [ASD(R&E) Basic Science/Labs, Arlington, VA July 30-31 2012]. One of the prominent ideas discussed was the use of low-flying aircraft as sources of sound for underwater acoustics applications, including target detection and bottom characterization, as investigated theoretically and experimentally by my research group at SIO over recent years[12].

TRANSITIONS

As previously reported.

RELATED PROJECTS

As previously reported.

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PATENTS

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HONORS/AWARDS/PRIZES

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